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(54) **Title:** FULL RANGE LOUDSPEAKER MODULE FOR PROVIDING SCALABLE LOUDSPEAKER SYSTEMS WITH VERTICAL AND HORIZONTAL BEAM STEERING CONTROL

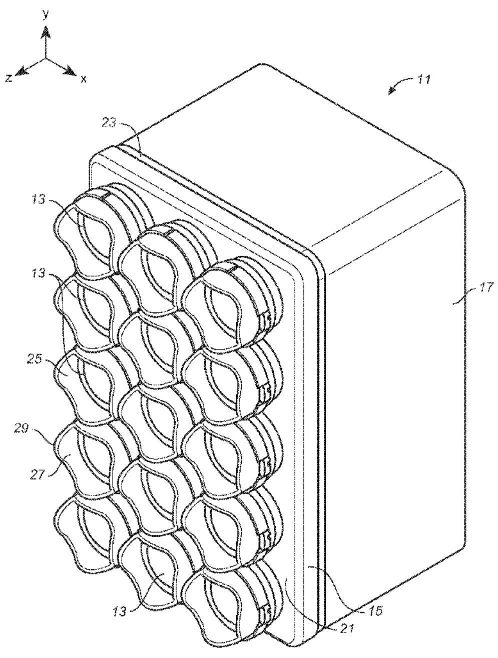

FIG. 1

(57) **Abstract:** A full frequency range loudspeaker module produces a steerable beam of acoustic energy and that can be readily configured with other similarly constructed modules to create a scalable loudspeaker system. The loudspeaker module is comprised of at least one low frequency transducer for producing a low frequency audio output a acoustically transparent mounting screen positioned in front of the low frequency transducer that supports a plurality of high frequency transducers in a two-dimensional array of high frequency transducers. The audio output from the low frequency transducer combines with the audio output of the high frequency transducers to produce a full range sound beam. Each transducer in the module is driven through a separate signal processing channel which provides the signal processing needed to steer the sound beam in a desired fashion. Modules can be combined for scalability and can be operated in either a loudspeaker mode or microphone mode.

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Full Range Loudspeaker Module for Providing Scalable Loudspeaker Systems with Vertical and Horizontal Beam Steering Control

Technical Field

[0001] The present invention relates to loudspeakers used for projecting reinforced sound into a space and more particularly to directional loudspeakers having a beam steering capability wherein the sound emitted by the loudspeakers can be directed into different regions of the space where the reinforced sound is needed. The present invention additionally relates to providing loudspeakers with a robust beaming steering capability in a full range system that is expandable to meet diverse applications in diverse locations and venues. The invention still further relates to loudspeaker systems that can behave in different modes for expanded capabilities such as providing for active sound cancellation where sound cancellation is desired.

Background Art

[0002] Loudspeaker systems having beam steering capabilities are well known. However, these systems typically operate other limited mid to high frequency ranges or have limited beam steering capabilities. For example, line array loudspeakers have been developed that have a beam steering capability, but the beam steering is only possible in one direction. U.S. Patent No. 8,238,588 discloses another type of loudspeaker system that has certain beam control features and provides for limited scalability but has a limited frequency range and beam steering capabilities. The present invention provides for a loudspeaker system that is scalable and operates over a broad frequency range and has more robust sound beam steering capabilities. The loudspeaker system of the invention is scalable in any direction and can be configured to create complex sound distribution patterns for placing sound in most any coverage area in front of the loudspeaker system and whose distribution patterns can be adjusted electronically without having to move or reconfigure the loudspeaker system.

Summary of the Invention

[0003] The invention is directed to a full frequency range loudspeaker module that produces a steerable beam of acoustic energy and that can be readily configured with other similarly constructed modules to create a scalable loudspeaker system. The loudspeaker module is comprised of at least one low frequency transducer for producing a low frequency audio output and a mounting screen positioned in front of the low frequency transducer that extends in an x-y plane perpendicular to the z-axis of the low frequency transducer. The mounting screen, which is acoustically transparent to the audio output from the low frequency transducer, supports a plurality of high frequency transducers which are affixed to the mounting screen in a two-dimensional array of high frequency transducers so as to provide a two-dimensional array of high frequency transducers in an x-y plane in front of the low frequency transducer. The high frequency transducers of the two-dimensional array of high frequency transducers are configured to form interstitial spaces between transducers through which the audio output from the low frequency transducer can propagate and combine with the audio output of the high frequency transducers.

[0004] Each of the high frequency transducers and the low frequency transducer have inputs for receiving signal inputs from a signal processor for controlling the magnitude and phase of the signal input to each transducer relative to the magnitude and phase for the signal inputs to other transducers. By controlling the magnitude and phase of the signal input to each transducer relative to the magnitude and phase for the signal inputs to other transducers, the combined outputs of the transducers produce a beam of sound that can be steered in the x or y direction about the z-axis of the low frequency transducer.

[0005] In another aspect of the invention, signal processing of one or more audio signal inputs is provided wherein each of the high frequency transducers and the low frequency transducer of the loudspeaker module has its own dedicated channel and wherein the magnitude and phase of the acoustic output from each transducer of the loudspeaker module can be separately controlled. By separately controlling the magnitude and phase of the plural acoustic outputs of the loudspeaker module or of a grouping of loudspeaker modules, different sound fields can be created in the 3-dimensional space in front of the loudspeaker module, including, for example, a narrow beam of sound that can be steered in both vertical and horizontal directions.

[0006] In still a further aspect of the invention the high frequency transducers and the low frequency transducer of the loudspeaker module can be switched between a loudspeaker mode and a microphone mode, wherein, when in the microphone mode, the transducer processes an audio signal capable of being processed and used to drive other transducers of the loudspeaker module or transducers of another loudspeaker module within a grouping of loudspeaker modules.

[0007] Further aspects of the invention will be appreciated from the following description of the illustrated embodiments of the invention.

Brief Description of the Drawings

[0008] Fig. 1 is a front perspective view of a full range loudspeaker showing a steerable high frequency transducer array module configured with a low frequency transducer in accordance with the invention.

[0009] Fig. 1A is an exploded front perspective view thereof.

[0010] Fig. 2 is a side elevational view thereof.

[0011] Fig. 3 is a front elevational view thereof.

[0012] Fig. 4 is a top plane view thereof.

[0013] Fig. 5 is a cross-sectional view thereof taken along lines 5-5 in Fig. 2.

[0014] Fig. 6 is a front perspective view thereof with the high frequency transducer array module removed and showing the low frequency transducer component and speaker mounting box for the low frequency transducer.

[0015] Fig. 7 is a front perspective view of the high frequency transducer array module of the loudspeaker shown in Fig. 1.

[0016] Fig. 8 is a side elevational view thereof.

[0017] Fig. 9 is a pictorial diagram illustrating the signal paths for driving the transducers of the loudspeaker illustrated in the foregoing drawings from a single signal input.

[0018] Fig. 10 is a pictorial diagram illustrating the signal paths for driving the transducers of the loudspeaker illustrated in the foregoing drawings from multiple signal inputs.

[0019] Fig. 11 is a pictorial diagram illustrating the signal paths for driving the transducers of the loudspeaker illustrated in the foregoing drawings from multiple signal inputs as in Fig. 10 and additionally illustrating a system feature wherein the loudspeaker can be switched from a loudspeaker mode into a microphone mode.

[0020] Fig. 12 is a pictorial diagram illustrating the signal paths for driving the transducers of two contiguous loudspeakers such as illustrated in Figs. 1-8 from multiple signal inputs and additionally illustrating a system feature wherein one to the two loudspeakers is switched to a loudspeaker mode and the other loudspeaker is switched into a microphone mode.

[0021] Fig. 13 is another pictorial diagram illustrating the signal paths for driving the transducers of two loudspeakers such as illustrated in Figs. 1-8 from multiple signal inputs and additionally illustrating a system feature wherein the output of the transducers of one loudspeaker operating in the microphone mode provides inputs to the other operating in the loudspeaker mode.

[0022] Fig. 14 is a pictorial diagram illustrating the components of the main processor shown in Figs. 9-12.

[0023] Fig. 15 is a pictorial diagram of the beam forming filter of the main processor shown in Fig. 14.

Best Mode for Carrying Out the Invention

[0024] The present invention is directed to a new loudspeaker module having a configuration of transducers that can provide a full range acoustic output in the form of a sound beam that is steerable in both the horizontal and vertical directions in real time. A loudspeaker module in accordance with the invention can be configured with other similarly constructed loudspeaker modules for scalability with respect to acoustic power and coverage requirements. The invention is additionally directed to a signal processing scheme for driving the transducers of the loudspeaker modules of the invention in a manner that realizes its real time beam steering capabilities. The signal processing schemes of the invention optionally include the ability to switch a selected loudspeaker module within a configuration of similarly constructed loudspeaker modules into a microphone mode. This feature can be used for noise cancelation and other applications.

[0025] Referring now to the drawings, Figs. 1-8 illustrate a full range loudspeaker module in accordance with the invention that can be configured with other similarly constructed modules as later described. The loudspeaker module, denoted by the numeral 11, includes a two-dimensional array of high frequency transducers 13 (sometimes referred to as herein as "hi drivers") mounted to the front 14 of a acoustically transparent mounting screen 15 that lies in an x-y plane perpendicular to the z-axis or radiation axis of the module. The mounting screen can be removably attached to the front face 18 of a loudspeaker module enclosure 17 by any suitable attachment means capable of holding the weight of the high frequency transducers, such as screw fasteners or removable push nut fasteners (not shown). As later discussed, selection of the perimeter shape of the module enclosure can facilitate the ability of the modules to be configured with other similarly constructed modules to create a loudspeaker system scaled up to meet particular venue requirements.

[0026] A low frequency transducer 19 (sometimes referred to herein as a "low driver") is mounted in enclosure 17 behind the mounting screen 15 so that it will project acoustic energy within its low frequency operating range out through the acoustically transparent mounting screen and the interstitial spaces 10 between the hi drivers. The acoustic outputs of the high frequency transducer array and the low frequency transducer situated behind the hi drivers combine to produce a full range acoustic output that projects from the front of the module and that as later described is capable of being steered any direction about the z-axis of the module.

[0027] As best shown in Fig. 1A, the hi driver mounting screen 15 is comprised of a thin acoustically transparent sheet material 21 secured to a perimeter frame 23. To achieve acoustical transparency, the sheet material has suitably sized openings 24 distributed throughout the material. (The preferred characteristics of these openings are later described.) The sheet material for the mounting screen is suitably a non-ferrous material, such as aluminum, stainless steel or plastic to prevent the mounting screen from effecting the magnetic circuits of the hi drivers. It will be understood, however, that use of ferrous sheet materials is within the scope of the invention. When using ferrous sheet materials for the mounting screen, attention may have to be given to shielding the magnet circuit of the hi drivers.

[0028] The acoustically transparent sheet material 21 of the mounting screen can be secured to perimeter frame 23 by any securement means such as by gluing, spot welding, or tacking the edges of the sheet material to the top or side surfaces of the frame. The perimeter frame that holds the sheet material can then be used to attach the mounting screen to the front face 18 of the module's enclosure 17 as described above.

[0029] While the openings 24 in the sheet material 21 of the mounting screen shown in Fig. 1A are round, the openings could be of any shape, including oval, hexagonal or square. Also, the acoustically transparent sheet material could be a stiff mesh material, such as a wire mesh screen that is sufficiently rigid to support the hi drivers.

[0030] It will be further understood that the hi driver mounting screen does not need to be 100% acoustically transparent for the loudspeaker module to perform effectively. As used herein, "acoustically transparent" means any degree of transparency that provides a significant enough amount of low frequency sound to meaningfully contribute to the full range output of the loudspeaker module. Preferably, the transparency will be greater than about 50% up to the cross-over frequency of the low driver, which can, for example, be up to about 1200 to 2000 Hz.

[0031] The desired screen transparency to sound emitted by the low frequency transducer 19 can be achieved by providing the sheet material 21 of the screen with large enough openings 24 and small enough spacings between openings. For example, openings in the support sheet material in the range of about ¼ inch to ½ inch with spacings no greater than about 1 inch, and preferably no greater than about ½ inch, would normally produce a mounting screen having suitable acoustic transparency. The screen's sheet material should be as thin as possible to avoid significant attenuation of the sound as it passes through the screen openings, but not so thin as to sacrifice the mechanical strength needed to support the hi driver array. Preferably, the acoustically transparent sheet material will have a thickness of no greater than about ¼ inch.

[0032] Each of the illustrated hi drivers is seen to have backplate 16 with a mounting screw hole 22 extending up through the bottom of the backplate. Using these mounting screw holes the hi drivers can be attached to the mounting screen 15 with fasteners such as screw fasteners (not shown). Other suitable means for securing the hi drivers to the acoustically transparent screen include, for example, using a front bezel (also not shown) that attaches to the perimeter frame 23 of the mounting screen so as to sandwich the hi drivers in place between the bezel and the acoustically transparent sheet material of the mounting screen. Wiring of the hi drivers can be accomplished through openings in the acoustically transparent sheet material.

[0033] Yet another screen in the form of an acoustically transparent loudspeaker grille screen can be provided for protecting the hi drivers. This grille screen (not shown) can be attached to the perimeter frame 23 of the mounting screen 15 or otherwise fixed in front of the hi drivers. It is contemplated that grille screens can be provided that will allow a thin 2-D configuration loudspeaker module to be used as a projection screen.

[0034] Examples of high frequency transducers 13 that can be used for the hi driver array of the illustrated loudspeaker module 11 are dome tweeters having a frequency range from about 1000 Hz to about 18 kHz and suitably sized between approximately about 25mm to about 35mm (or about 1.0 to about 1 3/8 inches) in diameter. The hi drivers are as closely spaced together as possible on the acoustically transparent sheet material of the mounting screen and in the drawings are shown as packed together so that they are nearly touching. The distance between the hi drivers plays an important role in beam control at the highest frequencies as the closely spaced hi drivers help reduce grating lobes. The smaller the separation between the drivers in the array the better the performance of the loudspeaker module will be. It noted that, despite their close spacing, the generally round configuration of the dome tweeter provides for interstitial open spaces 10 between the tweeters of the array through which the audio output from the low driver can propagate and combine with the audio output of the hi drivers.

[0035] It is noted that mounting the low frequency transducer behind the hi driver array opens the possibility of having a scalable planar array of hi drivers with no breaks needed within the hi driver array for the low frequency transducer. This makes a bigger array of hi drivers possible in a confined space and increases the operating range of the loudspeaker by adding low frequencies. In addition, as the number of modules increase in a configuration of individual loudspeaker modules, the composite loudspeaker system starts becoming directional at lower frequencies, providing the ability to steer the acoustic output of the composite system at lower and lower frequencies. Generally, the steerability of the low frequencies component of the acoustic output of the loudspeaker system will be proportional to the number of modules used in the configuration of the system.

[0036] The low frequency transducer 19 of the loudspeaker module 13 is suitably a four to five inch cone driver capable of producing an acoustic output at low frequencies up to about 1200 to about 1500 Hz. The spacing of the low driver behind the hi driver array is not critical but generally the low driver should be positioned close behind the hi driver array but not so close as to interfere with the excursions of the low driver diaphragm. The physical separation of the hi driver array and low driver can be compensated for in the signal processing for the loudspeaker system.

[0037] While it is contemplated that only a single low driver will be used in each loudspeaker module, it will be appreciated that a module in accordance with the invention can be constructed with more than a single low driver situated behind the hi driver array.

Additionally, loudspeaker modules in accordance with the invention could be combined with a larger cone driver, for example, with a 12 inch cone driver, to boost the acoustic output (power) of the loudspeaker system at low frequencies. Further, while the illustrated loudspeaker module enclosure 17 is shown as being relatively deep, the depth of the enclosure can be reduced to the minimum depth needed to support and conceal the low driver, suitably to a depth of about four inches or less. A shallower enclosure will result in a module more resembling a thin tile. And with a suitably rectangular perimeter shape as shown the tiles can be readily fitted together in a wide range of multi-tile patterns to achieve a wide range of different acoustic output patterns to meet a wide variety of coverage needs. It is contemplated that the tiles could have other straight-sided perimeter shapes that would allow them to be closely fitted together for scaling purposes, including triangular or hexagonal shapes. (As used herein rectangular is meant to include square.)

[0038] To achieve desired directional control over the acoustic output of a loudspeaker module 11 or a grouping of such modules, including minimizing side lobes or grating lobes, it is advantageous to provide for maximum isolation between neighboring hi drivers within the hi driver array of each module. To achieve this desired isolation, acoustical isolators 25 are provided for the hi drivers, preferably one for each hi driver. The illustrated acoustic isolators are seen to have a generally cylindrical shape with a cylindrical shroud wall 27 that projects out in front of and surrounds the hi driver to which it is attached. The forward projecting edge 29 of the shroud wall can be scalloped as shown or otherwise provided with an irregular shape to achieve desired results. The depth of the shroud wall is suitably in a range of about one-half inch to one inch. The precise depth and the forward edge characteristics of the isolators 25 needed to achieve best results can suitably be determined empirically by acoustic measurements is an anechoic chamber.

[0039] The number of drivers, including the low driver, used for each loudspeaker module is seen to be sixteen (fifteen hi drivers in a 3 by 5 array and one low driver behind the array). This preferred driver count has an advantage in the signal processing side for the loudspeaker module. Almost any digital transport protocol is divisible by 8 (16 is 8x2). While processed signal inputs can be either analog or digital, on the digital side it is advantageous to adhere to the AVB Milan protocol for input source. The AVB Milan protocol defines three stream format profiles for professional audio devices based on the IEEE 1722-2016 Standard AAF Audio Format:

- AAF Standard Stream Format (32 bit) Maximum 8 channels per stream
- High Capacity 32-bit Format Maximum 56 channels per stream
- High Capacity 24-bit Format Maximum 64 channels per stream

By adhering to this protocol, just a few source channels can be provided for all the transducers or as many source channels as desired can be sent to the output drivers in a matrix configuration.

[0040] The signal processing side of a loudspeaker system made up of loudspeaker modules such as above-described is now described with reference to Figs. 9-15.

[0041] Fig. 9 shows a simple signal processing scheme for driving the drivers of a single loudspeaker module or "tile" such as above described. In this representation, it is seen that there is a pictorial representation of a loudspeaker tile 11 having an array of fifteen high frequency transducers 13 and one low frequency transducer 19 supported behind the high frequency transducer array. Each of the transducers, including the low frequency transducer, is driven from an audio source passed through a front-end signal processing and amplification part of the system which is denoted by the numeral 12. More specifically, each of the transducers is seen to be connected to its own amplifier and signal processing channel so that the magnitude and phase of the acoustic output can be separately controlled to create virtually any desired wavefield (sometimes referred to as sound field) from the tile, including, for example, a narrow beam projecting anywhere in the 3-dimensional space in front of the tile, split beams or a wide pattern. It is contemplated that the front end signal processing and amplification part of the system will be physically incorporated into loudspeaker tile, but it could be located in a unit separate from the tile.

[0042] In Fig. 9 the signal processing channels and amplifiers include fifteen channels 31 with amplifiers 33 for the fifteen hi drivers 13 and a single channel 31a with amplifier 33a for the single low driver 19. The signal processing for each of these channels takes place through the main signal processor 35 of the processing and amplification part of the system as further described below. And in this illustrated case, the processed input from an audio source is from a single signal input 37, such as from a single microphone.

[0043] Fig. 10 shows the same multi-channel signal processing scheme for loudspeaker tile 11 as shown and described in Fig. 9 with the same front-end signal processing and amplification configuration 12. Except in this case, rather than coming from a single signal input as shown in Fig. 9, the audio source that feeds into the main signal processing function of the system comes from multiple signal inputs 37, in this case a signal input for each signal processing channel. Providing multiple signal inputs increases the flexibility of the system and provides greater latitude in creating sound coverages tailored to the needs of a particular application.

[0044] It is noted that the choice of sixteen channels is an advantageous choice where digital signal processing is used as computers work best in groups of eight channels (e.g. a byte is eight bits). The selected channel and transducer count could be in multiple eights for DSP processing, but the illustrated sixteen channels are considered to be an optimum number. Dedicating one of the channels to the low driver of the loudspeaker tile provides for a uniquely scalable, full range loudspeaker system with a robust acoustic beam control capability.

[0045] Fig. 11 illustrates the loudspeaker tile and the related signal processing of multiple input signals shown in Fig. 10 with an additional feature for switching the loudspeaker tile from a loudspeaker mode to a microphone mode. This feature recognizes that a loudspeaker can operate as a microphone if acoustic pressure of incident sound waves is allowed to move the diaphragms of the loudspeaker transducers. The sound waves will generate a time varying current within the affected transducers representing the detected acoustic waveform. This time varying current can then be amplified and used to drive the transducers of other loudspeaker tiles. Basically, this switching function turns the transducers of the loudspeaker tile from motors into generators.

[0046] To provide for switching the hi and low drivers 13, 19 of the loudspeaker tile 11 between a loudspeaker (PA) mode and microphone mode, a relay switch 39 is added in each channel of the system's front end 12 behind the channel amplifier. While for simplicity Fig. 11 shows this switch in just one of the channels, it will be understood that each channel will preferably be provided with a similar switch to permit the drivers of a single loudspeaker tile to be switched between modes. Suitably, all the drivers of a particular loudspeaker tile would be switched so that the entire tile is acting as either a loudspeaker or microphone;

however, applications where only selected drivers are switched from one mode to another are possible.

[0047] In Fig. 11 relay switch 39 is shown switched to the loudspeaker mode in that the output of amp 33 is connected to its associated hi driver 13. When switched to its other terminal position 41, the output of associated transducer 13, now operating as a microphone, is connected to a preamplifier 43, which acts to boost the signal before it is passed on to a microphone mode ("mic-mode") signal processor 45. The output 47 of the mic-mode signal processor can then provide signal inputs, such as signal input 38, for the main signal processor 35 for selected channels of the loudspeaker system where the drivers associated with the channels are in the loudspeaker mode.

[0048] Figs. 12 and 13 illustrate a mode switchable loudspeaker system such as shown in Fig. 11 adapted to a configuration of two loudspeaker tiles, with the tiles in Fig. 12 shown in a side-by-side configuration and the tiles in Fig. 13 separated. The configurations shown in these two figures are otherwise essentially the same. In each case, when in the loudspeaker mode, the loudspeaker tiles act is loudspeakers responsive to processed and amplified input signals 37 as well as to any additional input signals, such as input signal 38 provided by a loudspeaker tile operating in a microphone mode. If it noted the graphically illustrated main signal processor 35 is suitably a digital network that controls signal flows to and from all tiles on the network and the provide usable signal inputs to the drivers of any given tile on the network as represented by the usable signal output 40 in Figs 12 and 13.

[0049] Turning to Fig. 12 it is seen that one of the two side-by-side loudspeaker tiles, namely tile 11, is switched via relay switches 39 to the loudspeaker mode. In this mode the outputs of amps 33 feeding tile 11 (and from an amp for the low driver 19 which is not shown) are connected to their associated hi drivers 13 and low driver 19. These amplified signals are controlled by the main signal processor 35, which receive signal inputs from multiple signal inputs 37 and additional signal inputs 38 from tiles operating in the microphone mode. The other loudspeaker tile 11' shown in Fig. 12 shows how additional signal inputs 38 can be generated. Here the illustrated tile 11' is switched via relay switches 39a to the microphone mode. In this mode the outputs of amps 33, 33a feeding the loudspeaker tile are disconnected from the tile's hi drivers 13' and low driver 19'. Instead, the outputs of the hi and low drivers 13', 19', now operating as a microphones, are connected to a preamplifier 43, which acts to boost the signals before they are passed on to a microphone mode ("mic-mode") signal processor 45. The pre-processed microphone signal then provides a signal input for the main processor 35 as above-described.

[0050] Fig. 13 shows a very similar configuration with loudspeaker tile 11' being switched to the microphone mode via relay switches 39a and loudspeaker tile 11 being switched to a loudspeaker mode via relay switches 39. Again, each tile driver 13, 19 and 13', 19' has its own channel with associated signal processing and amplification capabilities, such as via amps 33 and 33a. As described below, the main processor 35 is most suitably a digital network for providing digital signal processing capabilities. Needed analog-to-digital and digital-to-analog convertors (not shown) can be provided by well-known circuit elements and processing techniques.

[0051] Figs. 14 and 15 show an exemplary filtering scheme for the main signal processing for achieving desired beam or acoustic output control from a loudspeaker module or grouping of loudspeaker modules described above. Referring to Fig. 14, the main signal processing, denoted by block 48 is most suitably achieved via digital signal processing (DSP). This processing is comprised of two main parts, a linear filtering section 49 and a non-linear filtering section 51. The linear filtering section contains linear time invariant (LTI) filter blocks comprised of a high-pass filter section 53, a low-pass filter section 55 and a beamforming filter 57. (All filtering is done digitally. There is no "analog" audio section, however, many digital LTI filters can be based on analog designs.)

[0052] The high-pass and low-pass filter sections 53, 55 ("cross-over filter blocks") are designed to allow for the band-limiting required for audio crossovers, i.e. band-limiting a broadband input signal into a bandpass signal suitable for the targeted transducer. In traditional loudspeaker design, low-order IIR (infinite impulse response) type DSP filters are used, but a loudspeaker module in accordance with the invention has many "operating modes", and so this section might use traditional IIR as well as Finite Impulse Response (FIR) filters. The crossover filter blocks 53, 55 will typically be "static", i.e. the parameters are developed during product testing, and would not normally be available for the user to change.

[0053] The crossover filter blocks can also contain DSP filters based on classic 2nd order biquads for traditional loudspeaker equalization needs, as well as room equalization for controlling audio interactions between loudspeaker modules 11 and the existing acoustics at the venue at which the system is used, such as a room or auditorium.

[0054] The second main component of the linear filtering section is the beam forming filter section 57. The filter parameters for the filter section will be generated and updated in real-time. This allows for the loudspeaker tiles 11 to create real-time sound beams, which can move around physical space in real time. The loudspeaker tiles 11 can create bespoke acoustical coverage patterns, usually designed to increase intelligibly in highly reverberant rooms. For example, the beam forming parameters would direct all of the acoustic energy toward the listening area, keeping the sound from reflecting off of walls or ceiling of a room, limiting the reverb or "boominess" of the sound. This DSP block will contain a general purpose DSP engine, allowing for simultaneous generation of IIR, FIR, and Convolution filter blocks, depending on the application.

[0055] A more general type of beam forming is known as "wave field synthesis." Essentially, wave field synthesis allows for the creation of arbitrary wave fields. The above-described loudspeaker tiles are most suitably form 2-D "tiled" loudspeaker systems. For low frequency wave field synthesis, many tiles will be assembled together. The tiles need not be continuous; for example, a checkerboard pattern might be required for a particular application.

[0056] Another use of the beam forming DSP block will be active sound cancellation. Where each loudspeaker tile can be switched as above-described between loudspeaker or "PA" mode and microphone mode or mic-mode, the beam forming DSP block can perform active sound cancellation. The tiles that are in mic-mode will listen for particular sounds, and the real-time wave field synthesis DSP engine will create filter coefficients that create an inverse wave, thereby allowing for active sound cancellation, as well as other forms of active sound control.

[0057] The non-linear filter section 51 of the main signal processing section is comprised of DSP implementations of classical limiting and compression algorithms. The main use of these filter blocks is transducer protection—i.e., limiting SPL to protect the transducers from over-excursion (Peak Limiting Transducer Protection block 59), or RMS limiters to limit the long-term heating of the voice coils, etc. (RMS Compression and RMS Limiting blocks 61, 63). However, these non-linear DSP blocks might also have applications for traditional audio signal processing. For examples, in a voice based PA system, compression algorithms can sometimes improve intelligibility in highly-reverberant environments.

[0058] The main signal processing block also contains the DSP necessary for microphone processing from, for example, microphone inputs from relay controlled modules 11 operating in the microphone mode, as denoted by block 65. The microphone processing contains the same elements as the "PA" signal processing (IIR, FIR, Convolution), but might contain higher order algorithms as well, application depending. For room acoustic applications, FFT based transfer function estimation will be useful (SIM algorithms). Machine learning and convolution neural networks will be useful for active sound cancellation, since it would then be possible for the loudspeaker systems made up of modules or tiles as above-described to "learn" which sounds to cancel, and which not to cancel. For example, networked loudspeaker tiles in accordance with the invention could be made to learn the sound of the voices of performers, while actively cancelling out the voices of audience members.

[0059] Fig. 15 graphically shows an exemplary configuration for the beam forming filter 57 having 16 channels, denoted channels 1 through 16. Each filter channel is comprised of a long FIR filter, denoted by filter blocks 67, which can be used in a sixteen channel loudspeaker module or tile in accordance with the invention. As noted in Fig. 15, the coefficients for each of the long FIR filters suitably would have in the range of 8000 taps and, as denoted by block 70, would be updated in real time as described above.

[0060] While various embodiments of the invention have been described in considerable detail in the foregoing specification, it will be appreciated that variations on the illustrated and described embodiments would be apparent to a person skilled in the art and within the scope of the invention.

WE CLAIM:

1. A full frequency range beam steerable loudspeaker module for creating scalable loudspeaker systems, comprising

at least one low frequency transducer for producing a low frequency audio output and having a z-axis,

a mounting screen positioned in front of the low frequency transducer and extending in an x-y plane perpendicular to the z-axis of the low frequency transducer, the mounting screen being acoustically transparent to the audio output from the low frequency transducer, and

a plurality of high frequency transducers affixed to the mounting screen so as to provide a two-dimensional array of high frequency transducers in an x-y plane in front of the low frequency transducer, the high frequency transducers of the two-dimensional array of high frequency transducers being configured to form interstitial spaces between the high frequency transducers through which the audio output from the low frequency transducer can propagate and combine with the audio output of the high frequency transducers,

each of the high frequency transducers and the at least one low frequency transducer being configured to receive signal inputs for controlling the magnitude and phase of the signal input to each transducer relative to the magnitude and phase for the signal inputs to other transducers, wherein, by controlling the magnitude and phase of the signal input to each transducer relative to the magnitude and phase for the signal inputs to other transducers, the combined outputs of the transducers produce a beam of sound that can be steered in the x or y direction about the z-axis of the low frequency transducer.

2. The loudspeaker module of claim 1 further comprising an enclosure having a front face and perimeter shape, and wherein the low frequency transducer is mounted in said enclosure so that the low frequency audio output produced by the low frequency transducer propagates out from the front face of the enclosure and the mounting screen with the high frequency transducers affixed thereto is attached to the front face of said enclosure over the low frequency transducer.

3. The loudspeaker module of claim 2 wherein said loudspeaker enclosure is configured such that similarly constructed loudspeaker modules can be fitted together to create a scaled-up loudspeaker system.

4. The loudspeaker module of claim 3 wherein the enclosure has a straight-sided perimeter shape.

5. The loudspeaker module of claim 1 further comprising acoustic isolators placed over and surrounding the high frequency transducers mounted to the mounting screen for isolating one high frequency transducer from neighboring high frequency transducers within the array of high frequency transducers of the loudspeaker module.

6. The loudspeaker module of claim 5 wherein the acoustic isolators project forwardly from the high frequency transducers to a distance of between about ½ inch and about one inch.

7. The scalable beam steerable loudspeaker module of claim 5 wherein the acoustic isolators project forwardly from the high frequency transducers and have a forward leading edge that is irregularly shaped.

8. The loudspeaker module of claim 1 wherein the total number of transducers for the loudspeaker module, including high frequency transducers and at least one the lower frequency transducer is a multiple of eight including 1 X 8.

9. The loudspeaker module of claim 1 wherein the total number of transducers for the loudspeaker module, including high frequency transducers and at least one the lower frequency transducer is 16.

10. The loudspeaker module of claim 9 wherein the total number of high frequency transducers in the two-dimensional array of high frequency transducers is 15 and for the loudspeaker module and the number of low frequency transducers is one.

11. The loudspeaker module of claim 9 wherein the two-dimensional array of high frequency transducers is a 3 by 5 array of transducers.

12. The loudspeaker module of claim 1 wherein the mounting screen for the high frequency transducers include an acoustically transparent sheet material and wherein the high frequency transducer material are affixed to said sheet material.

13. The loudspeaker module of claim 12 wherein the acoustically transparent sheet material is a non-ferrous material.

14. The loudspeaker module of claim 12 wherein the degree of transparency of the acoustically transparent sheet material is greater than 50%.

15. The loudspeaker module of claim 1 further comprising means for switching at least one of said high frequency transducers from a mode wherein the transducer is behaving as a loudspeaker in response to a signal input and a mode wherein the transducer is behaving as a microphone for producing a signal output that can be used to provide a signal input for a transducer of another loudspeaker module.

16. The loudspeaker module of claim 1 further comprising means for switching all of the high frequency transducers and at least one low frequency transducers from a mode wherein all the transducers of the loudspeaker module are behaving as a loudspeaker in response to signal inputs and a mode wherein all of the transducers are behaving as a microphone for producing signal outputs that can be used to provide a signal inputs for the transducers of another loudspeaker module.

17. A full frequency range beam steerable loudspeaker module for creating scalable loudspeaker systems, comprising

enclosure having a front face and configured such that similarly constructed loudspeaker modules can be fitted together to create scaled-up loudspeaker systems, an acoustically transparent mounting screen attached to the front face of said enclosure,

a plurality of high frequency transducers affixed to the mounting screen so as to provide a two-dimensional array of high frequency transducers in an x-y plane in front of front face of the enclosure, and

at least one low frequency transducer mounted in said enclosure for directing a low frequency audio output out through the mounting screen with the high frequency transducers affixed thereto,

the high frequency transducers of the two-dimensional array of high frequency transducers being configured such that the audio output from the at least one low frequency transducer can propagate through the array of high frequency transducers so as to combine with the audio output of the high frequency transducers, and

each of the high frequency transducers and the at least one low frequency transducer being configured to receive signal inputs for controlling the magnitude and phase of the signal input to each transducer relative to the magnitude and phase for the signal inputs to other transducers, wherein, by controlling the magnitude and phase of the signal input to each transducer relative to the magnitude and phase for the signal inputs to other transducers, the combined outputs of the transducers produce a beam of sound that can be steered in the x or y direction about the z-axis of the low frequency transducer.

18. The loudspeaker module of claim 17 wherein said enclosure is a straight-sided enclosure allowing the module to be fitted together with other similarly constructed loudspeaker modules to create scaled-up loudspeaker system.

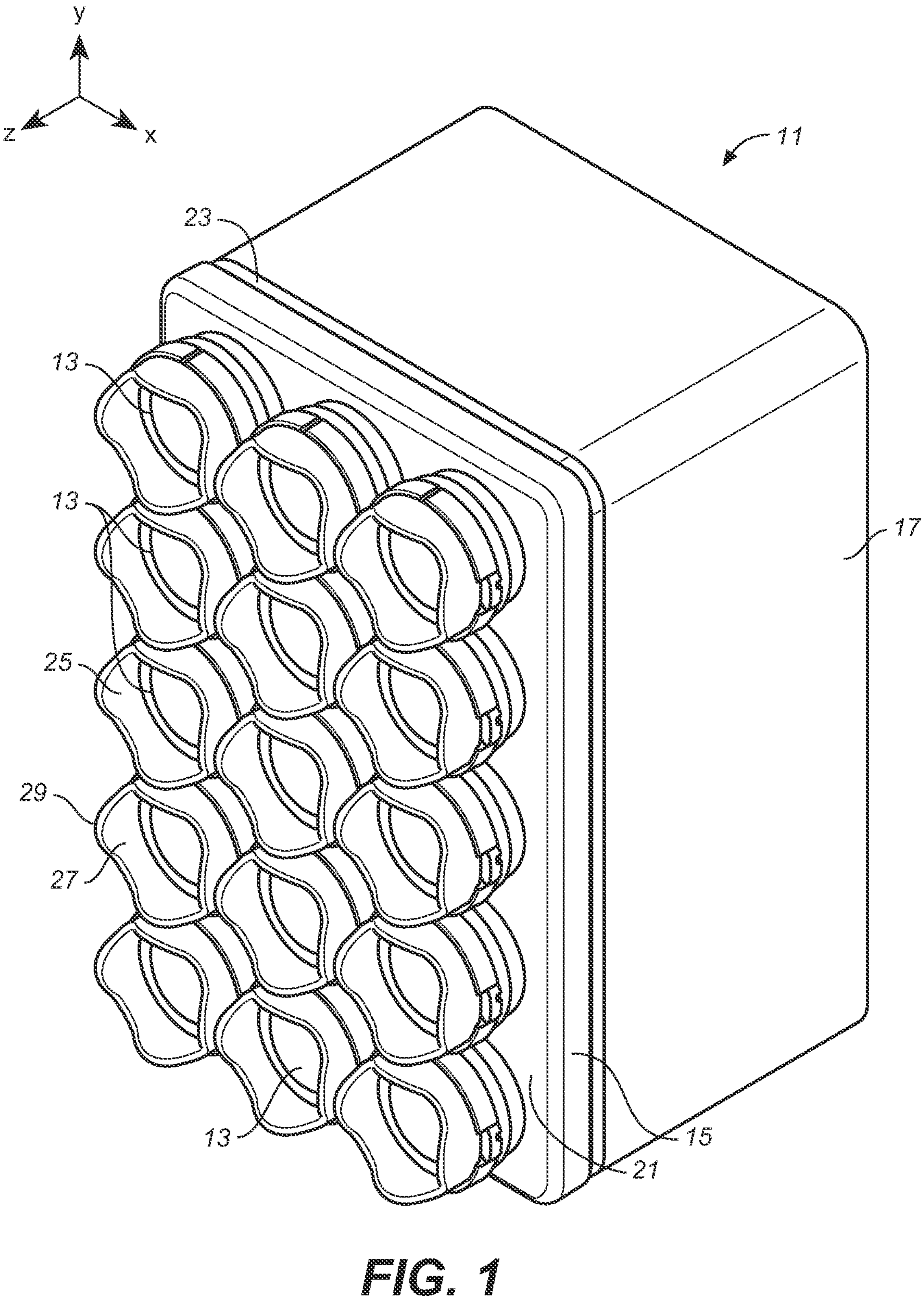

FIG. 1

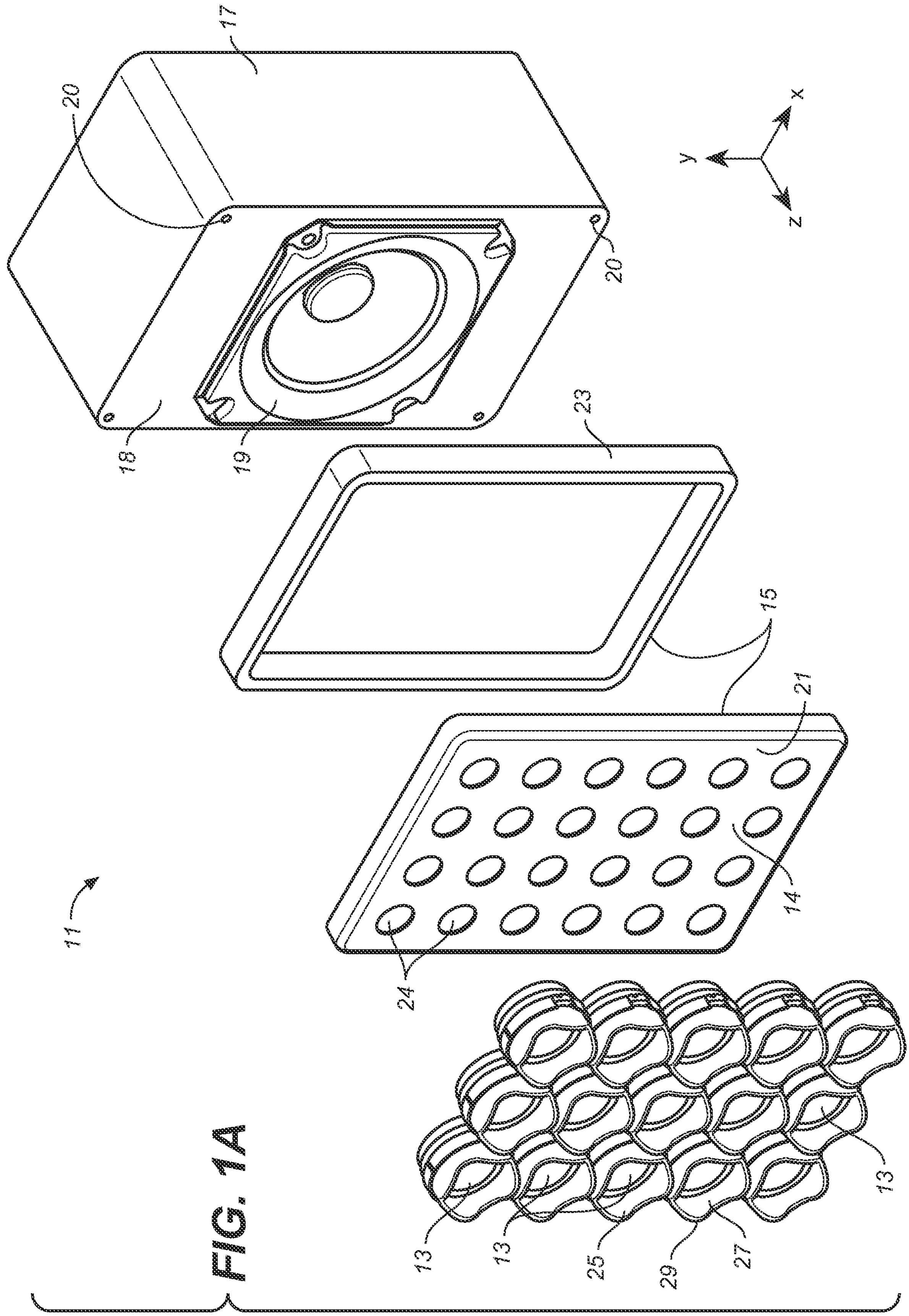

FIG. 1A

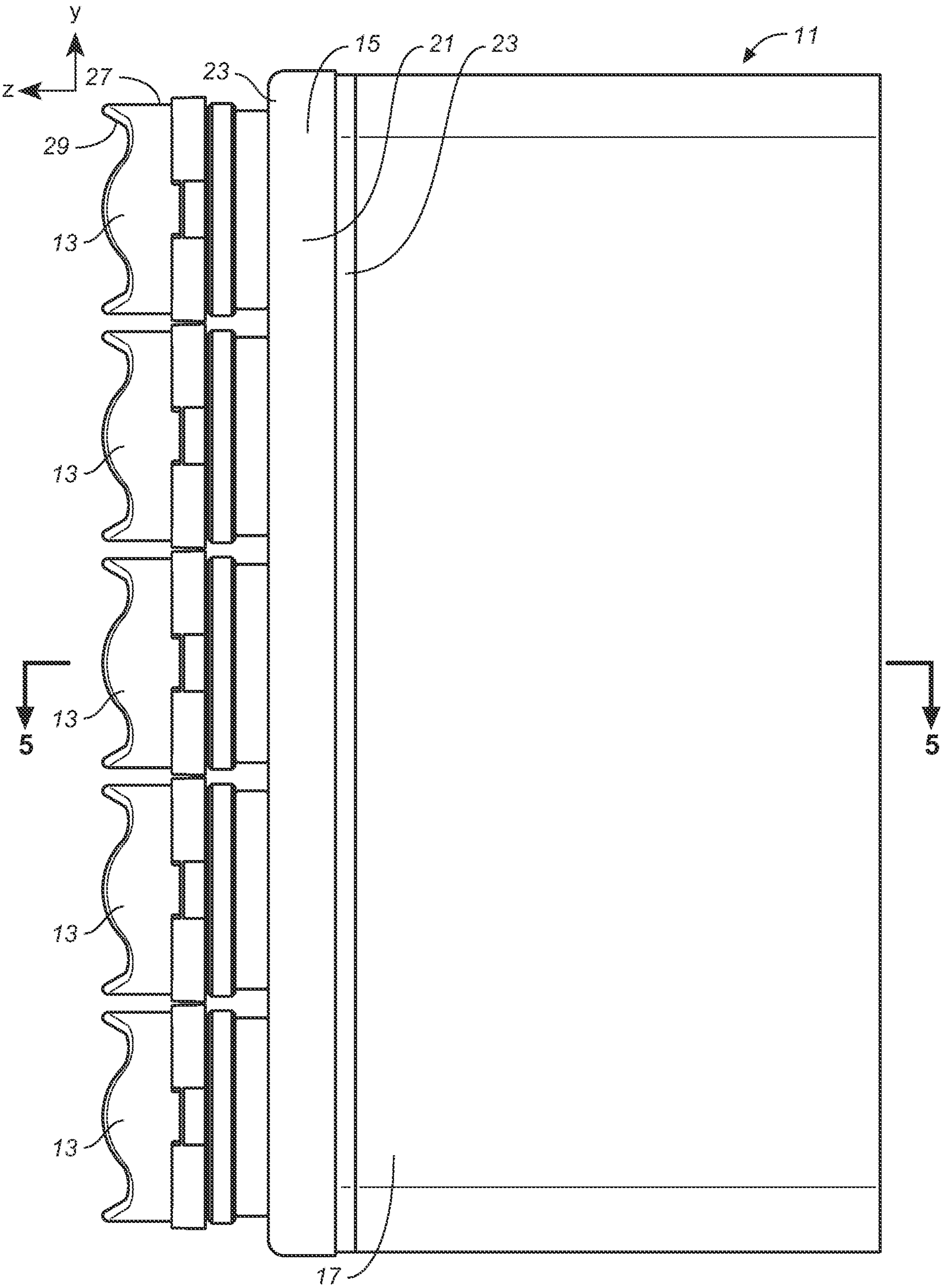

FIG. 2

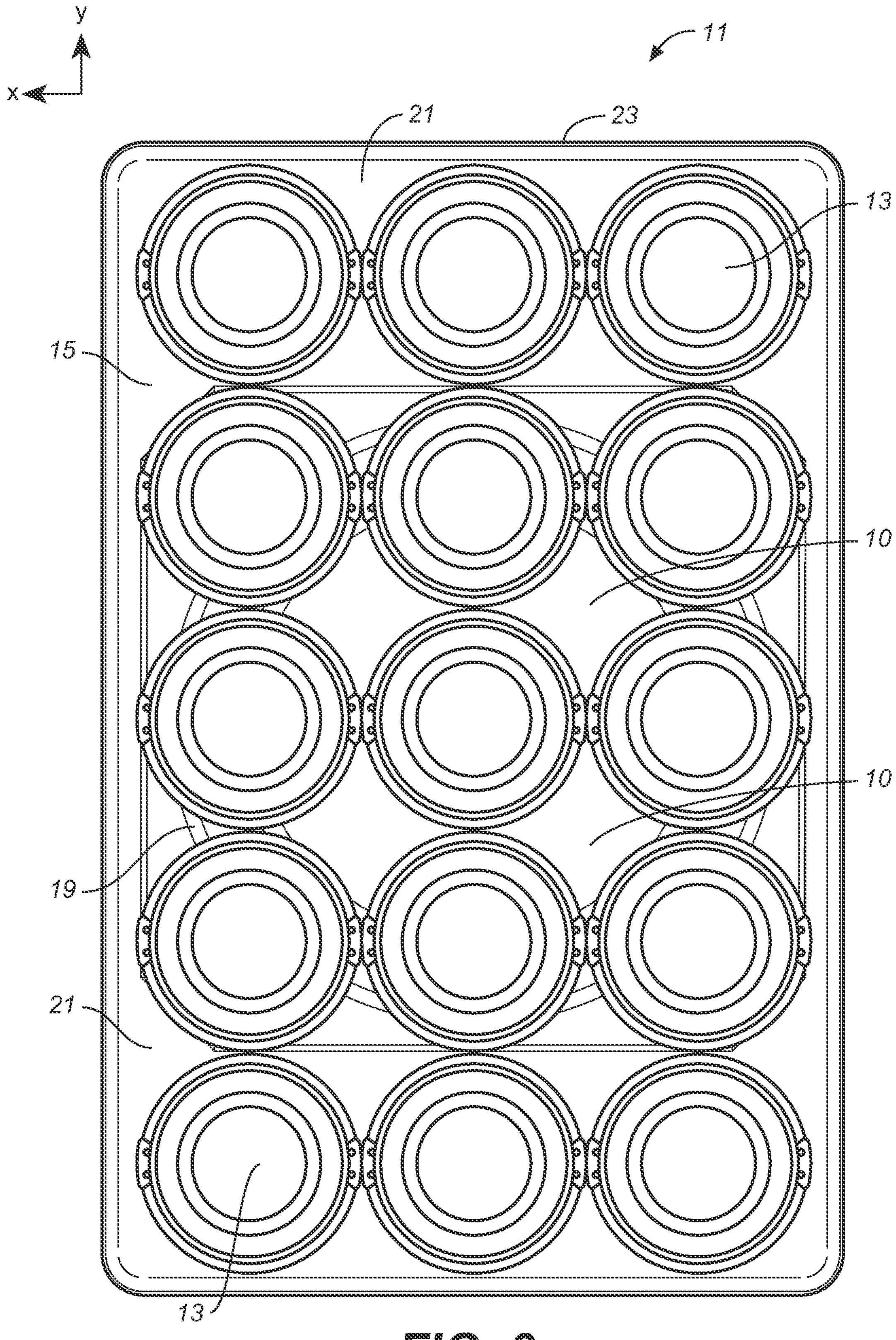

FIG. 3

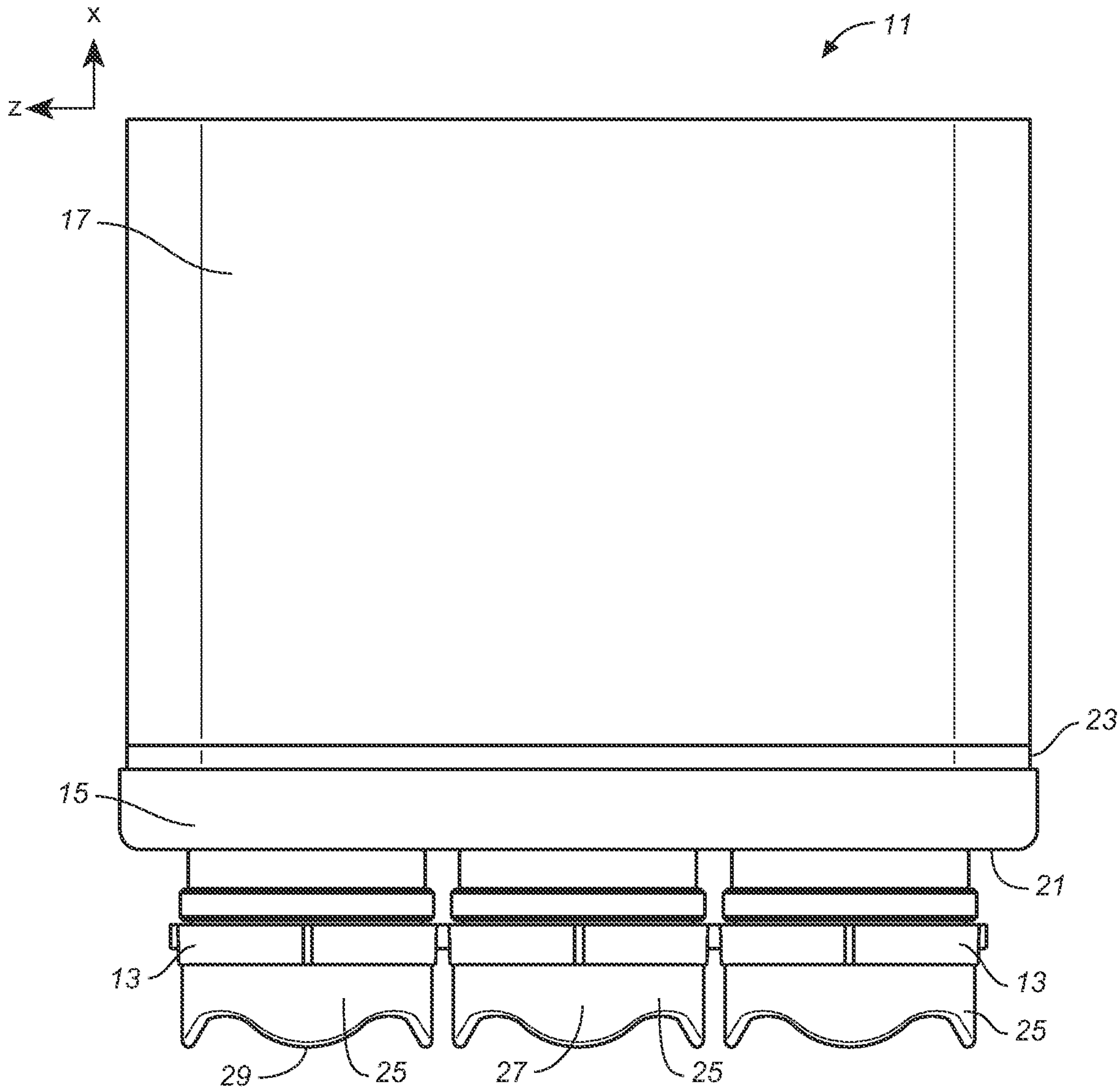

FIG. 4

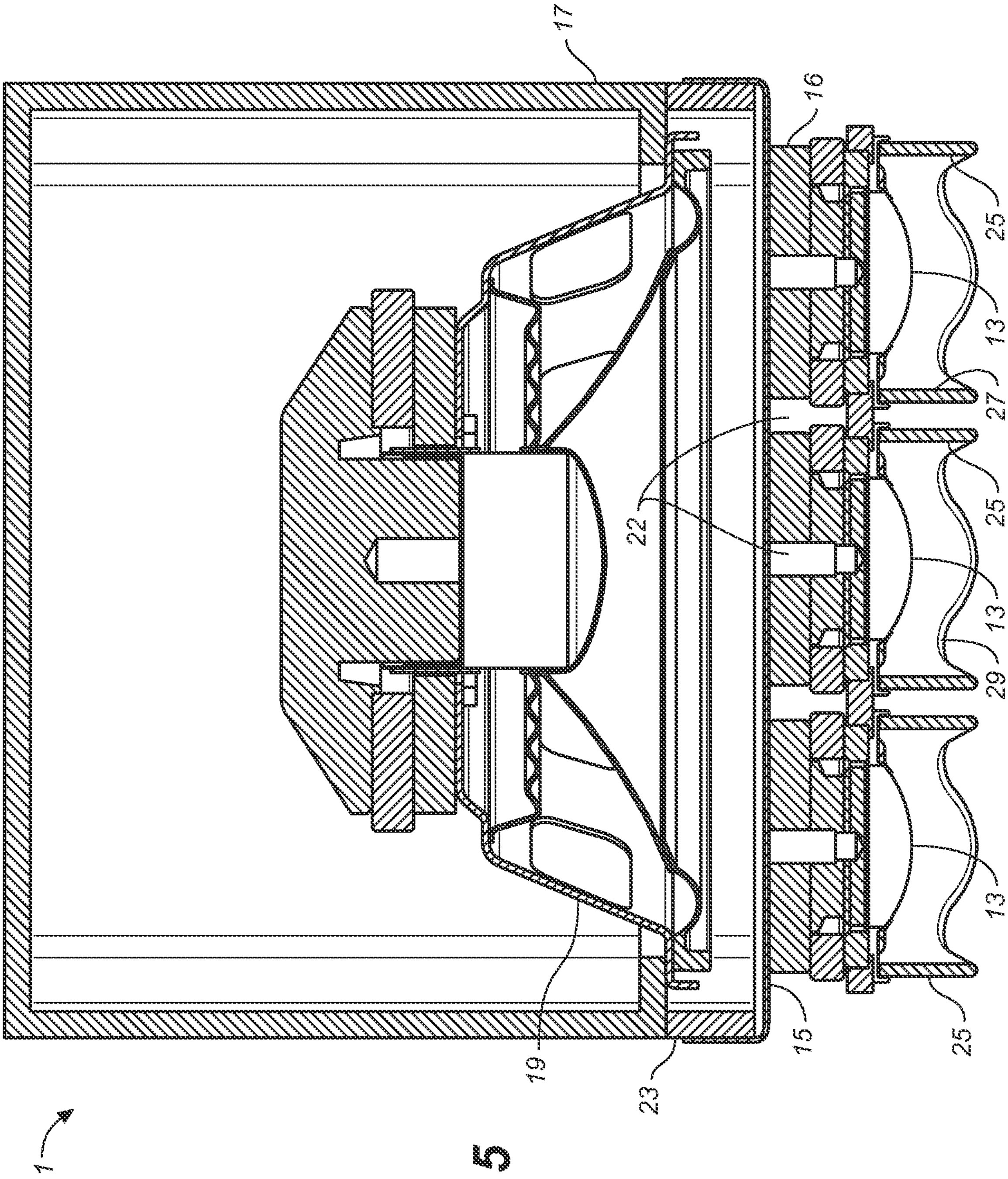

FIG. 5

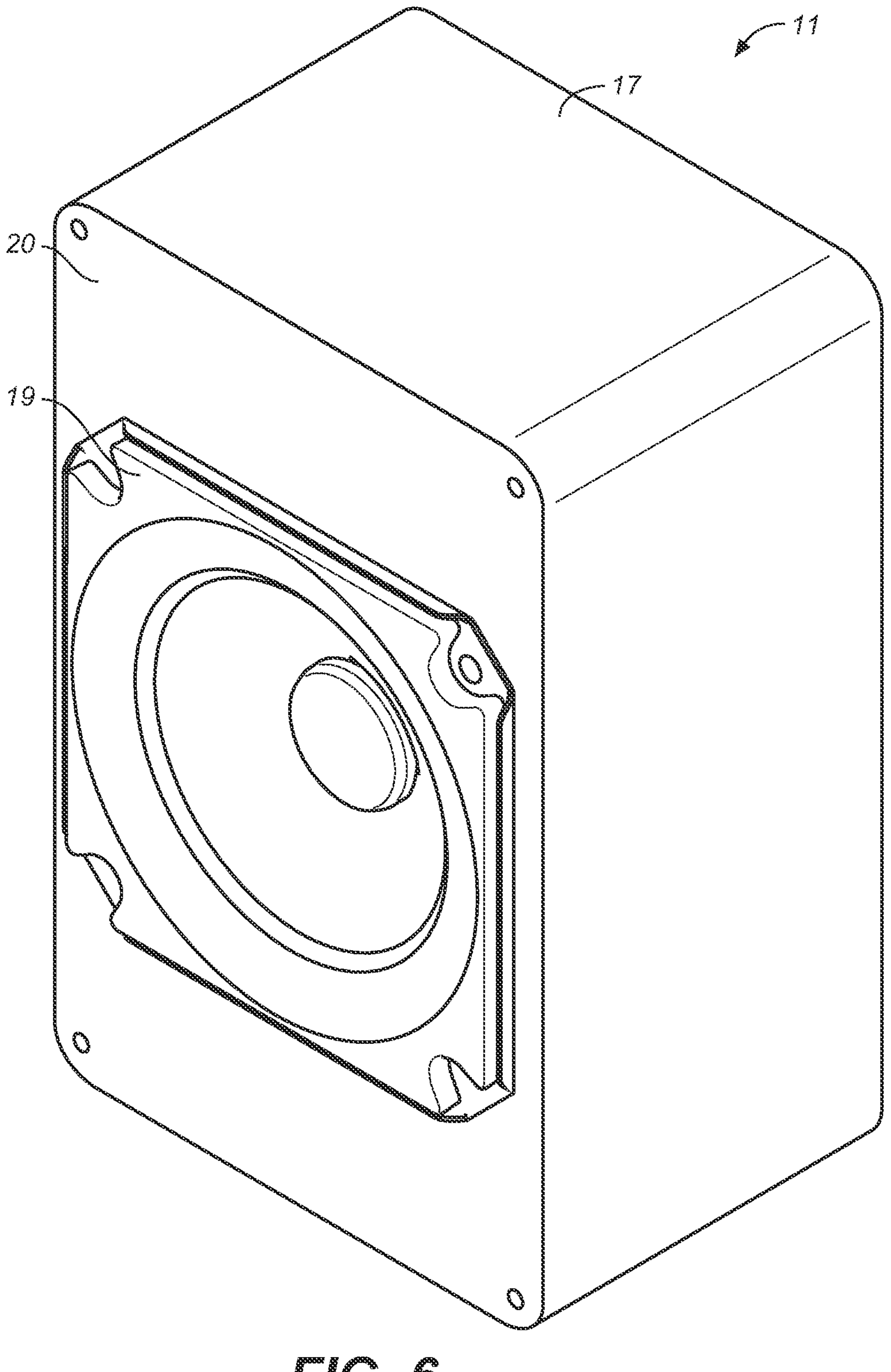

FIG. 6

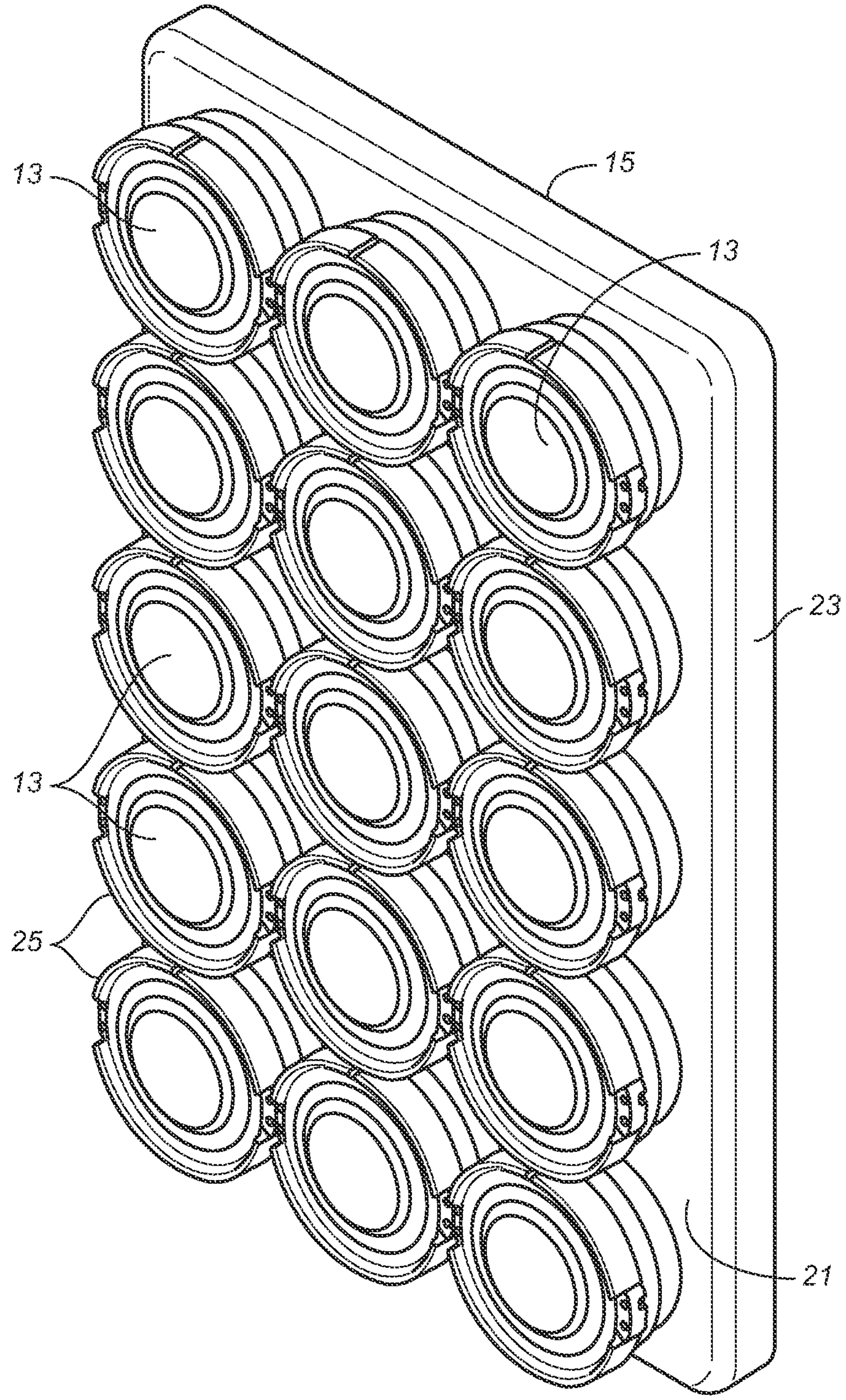

FIG. 7

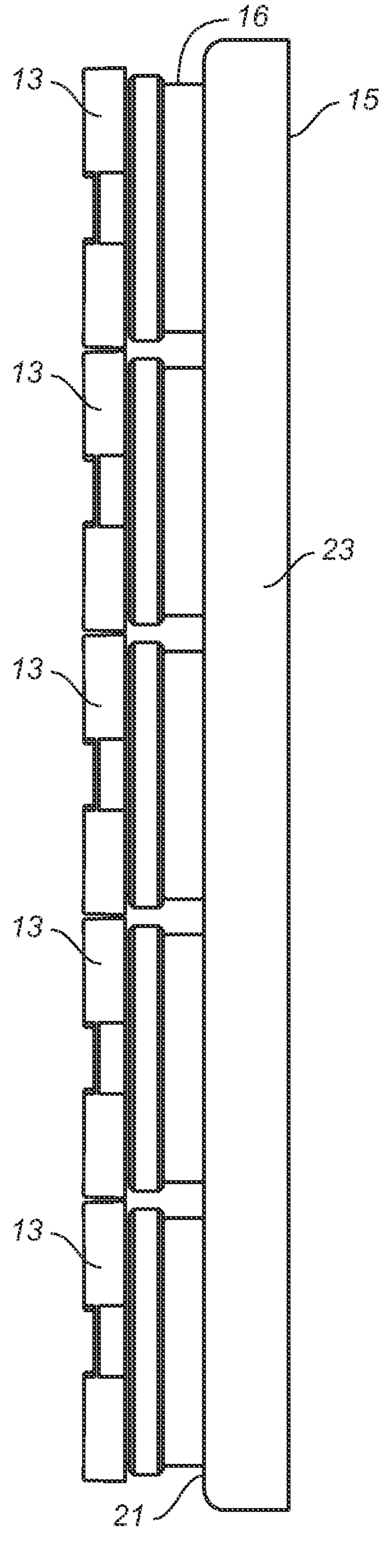

FIG. 8

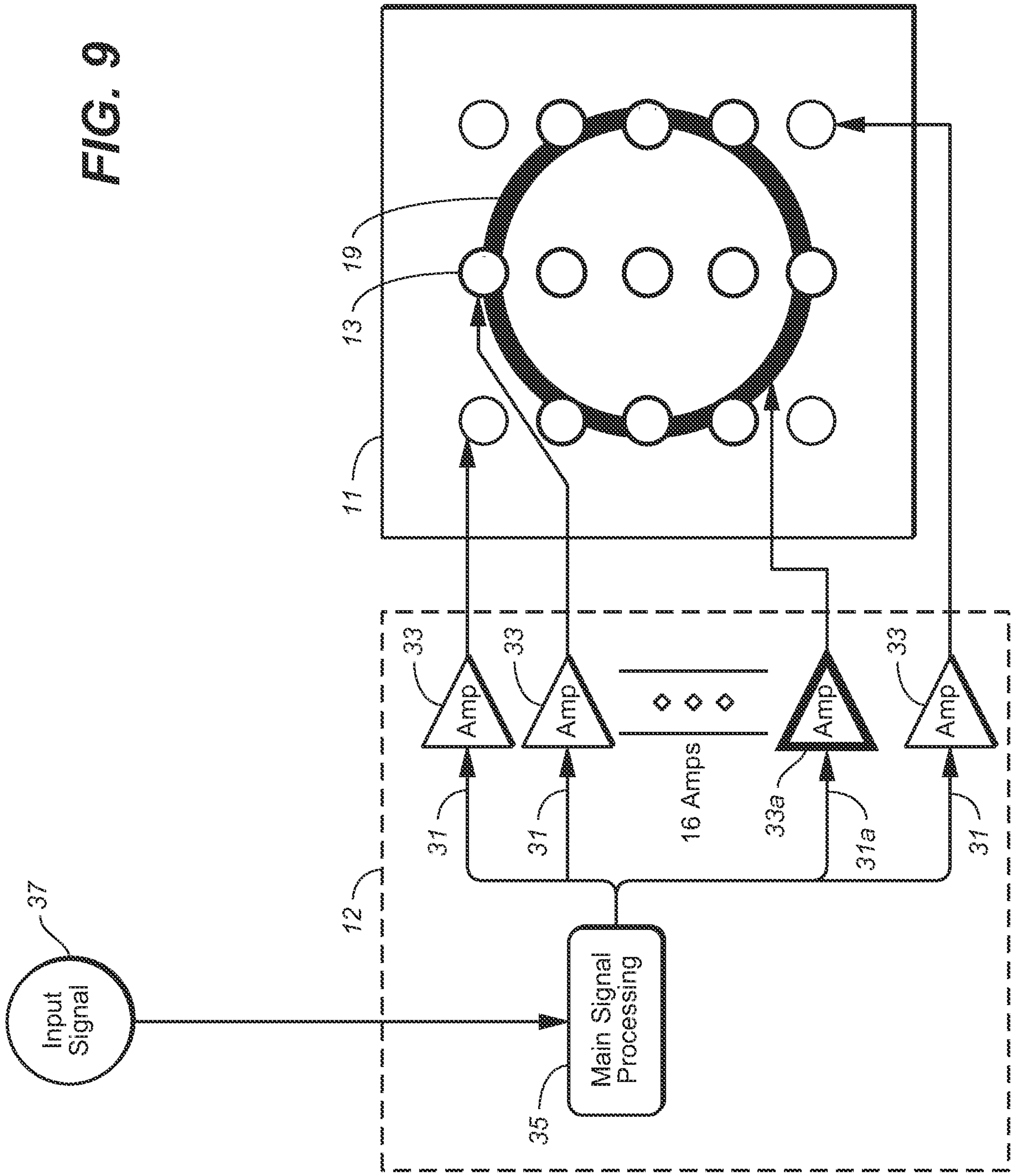
19
13
11
33
33
33
33
Amp
Amp
Amp
Amp
16 Amps
33a
31
31
31a
31
12
37
Input Signal
Main Signal Processing
35

FIG. 9

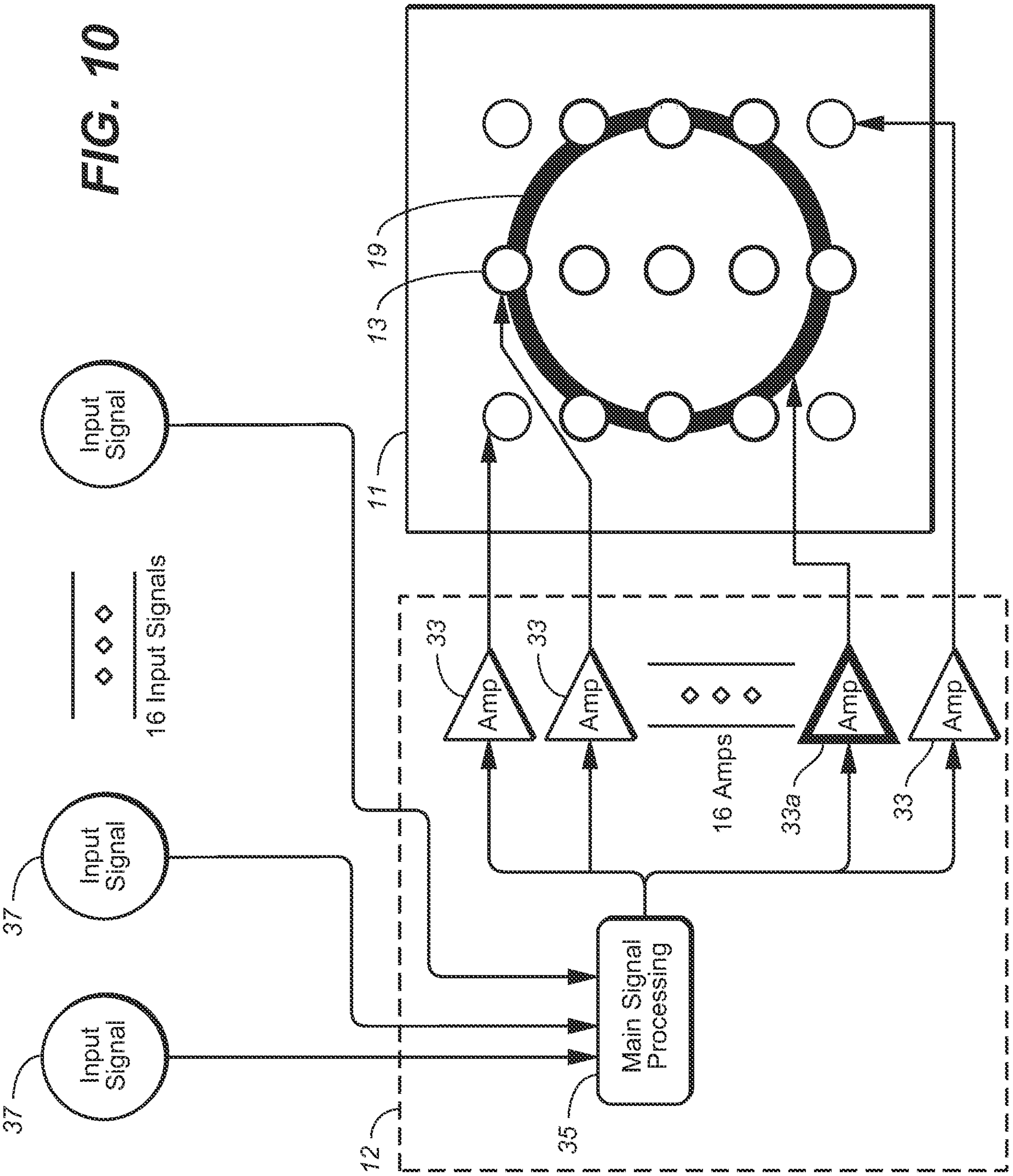
Input Signal
Input Signal
Input Signal
37
37
16 Input Signals
11
13
19
Amp
Amp
Amp
Amp
33
33
33a
33
16 Amps
Main Signal Processing
35
12

FIG. 10

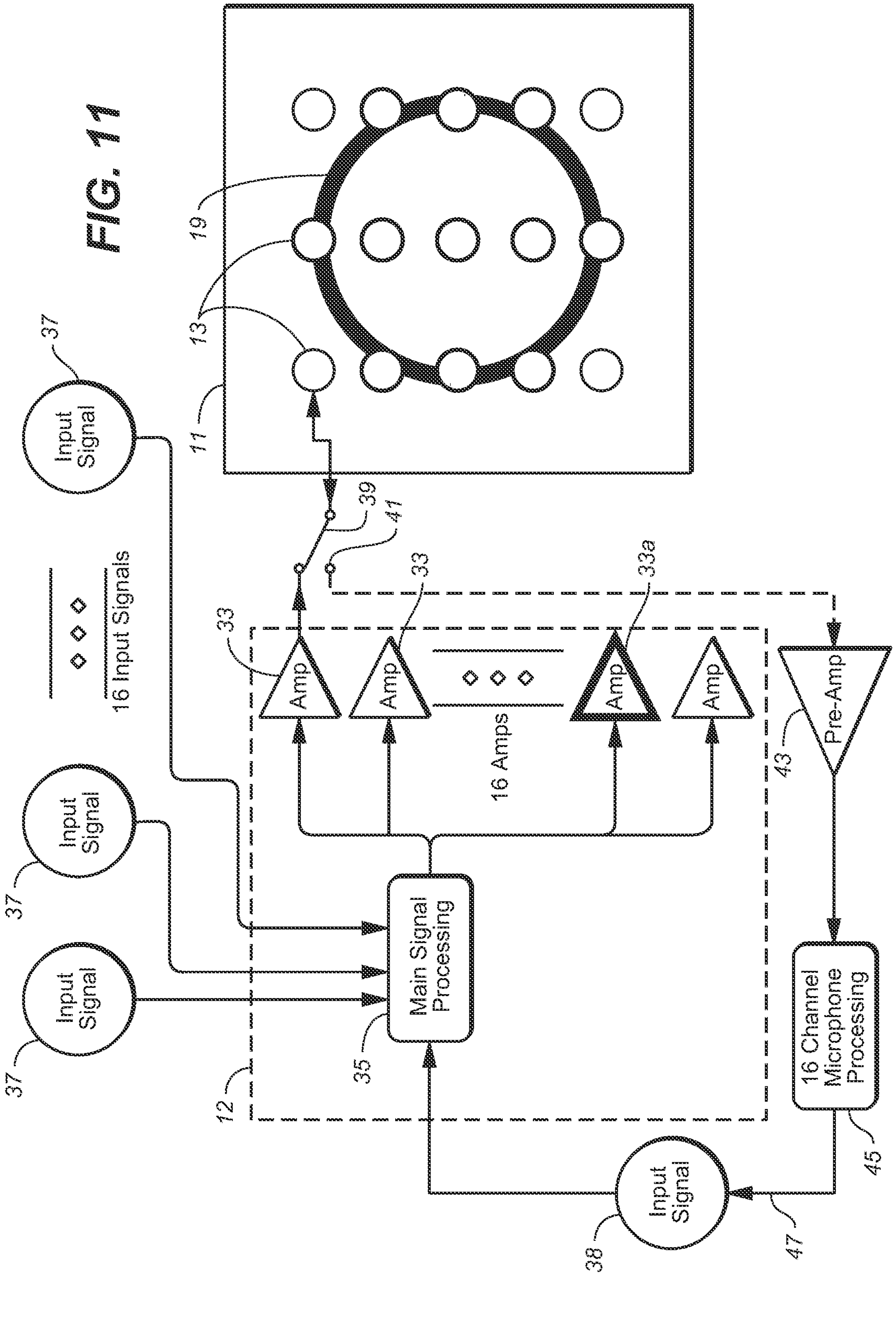
Input Signal
Input Signal
Input Signal
37
37
37
16 Input Signals
Main Signal Processing
35
12
16 Amps
Amp
Amp
Amp
Amp
33
33
33a
39
41
Pre-Amp
43
16 Channel Microphone Processing
45
Input Signal
38
47
11
13
19

FIG. 11

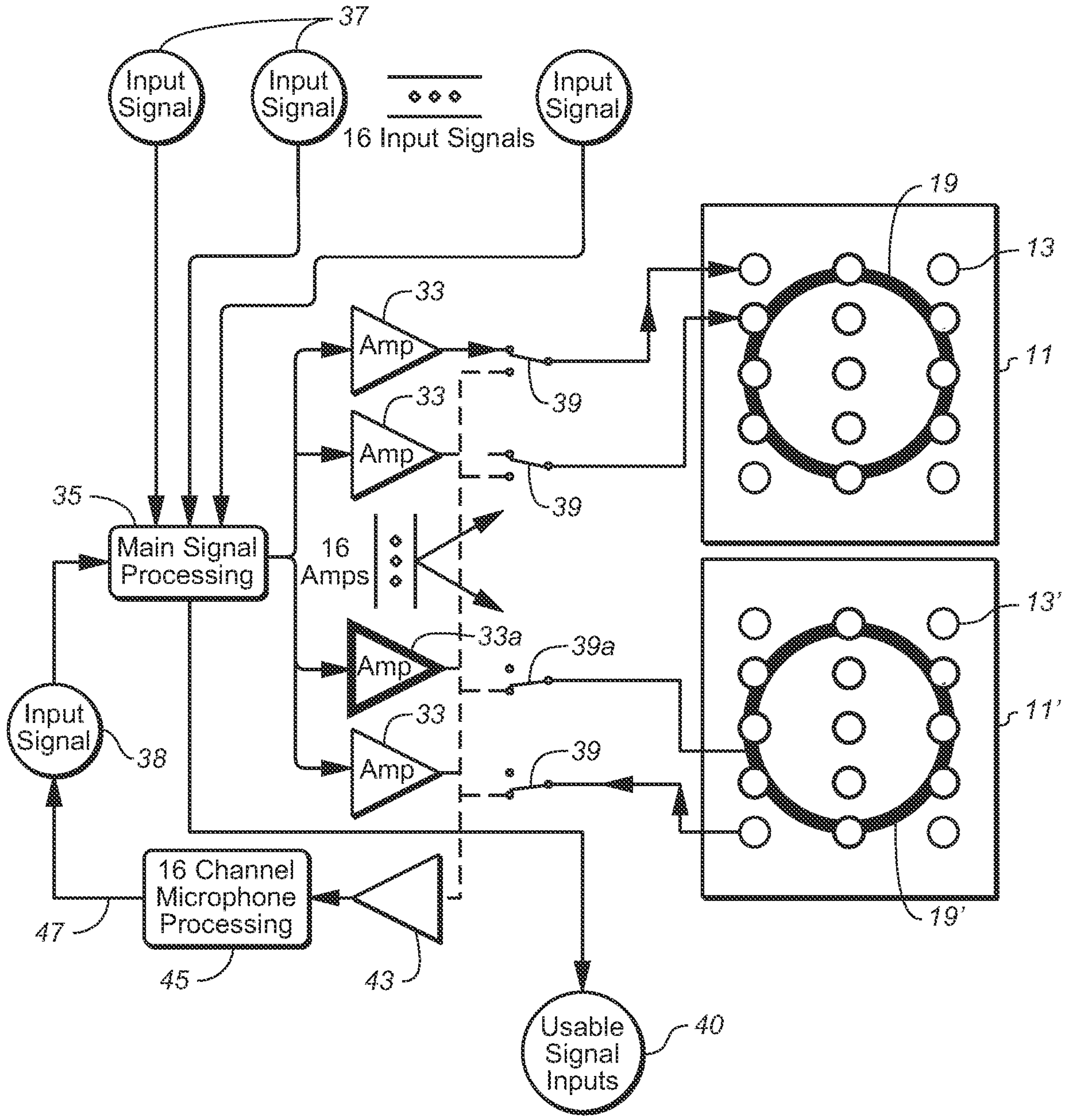
37
Input Signal
Input Signal
16 Input Signals
Input Signal
19
13
33
Amp
11
39
33
Amp
39
35
Main Signal Processing
16 Amps
13'
33a
Amp
39a
11'
Input Signal
38
33
Amp
39
16 Channel Microphone Processing
19'
47
45
43
Usable Signal Inputs
40

FIG. 12

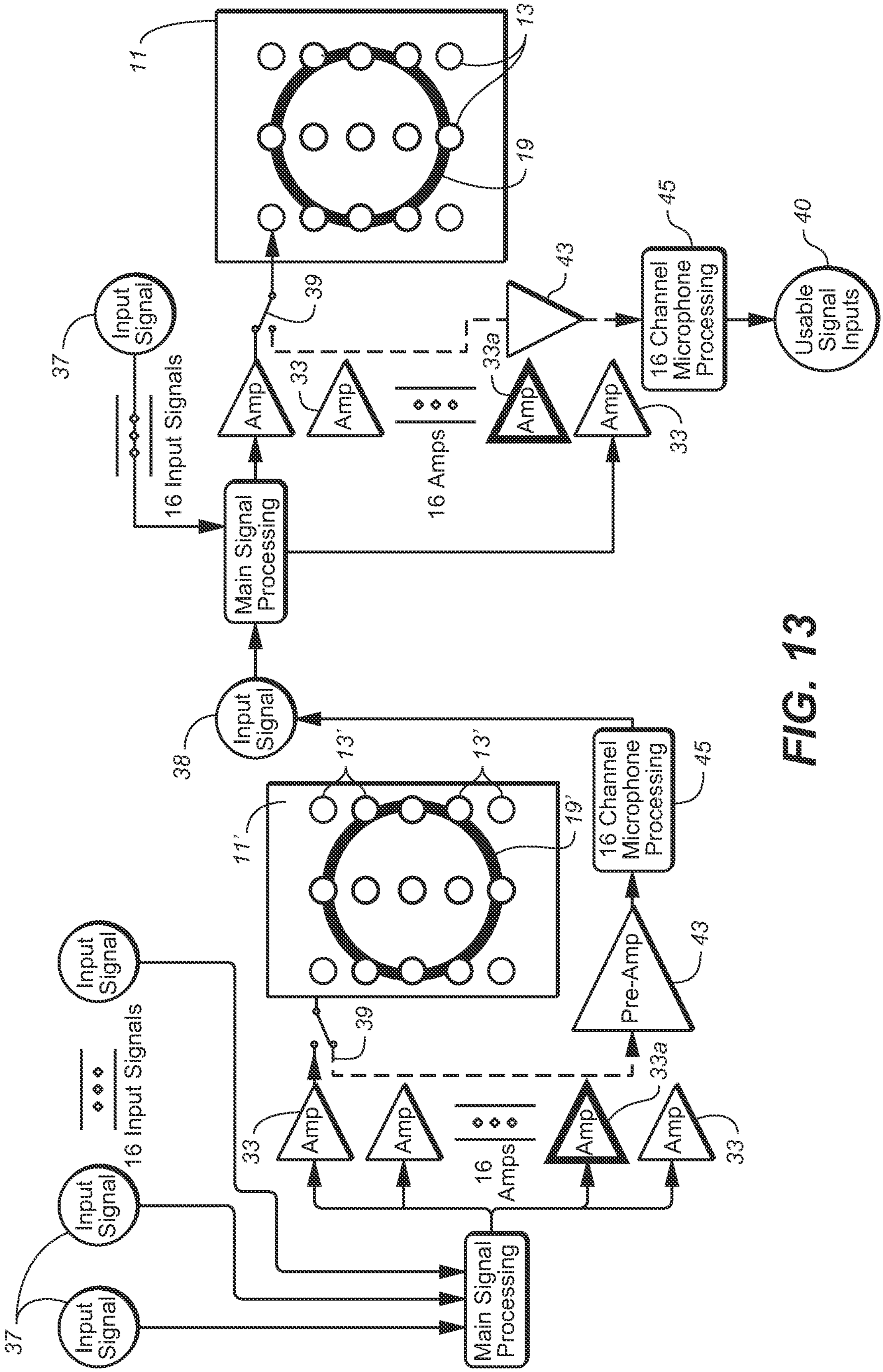
11
13
19
37
Input Signal
16 Input Signals
Main Signal Processing
Amp
33
39
33a
43
45
16 Channel Microphone Processing
40
Usable Signal Inputs
16 Amps
38
11'
13'
19'
Pre-Amp

FIG. 13

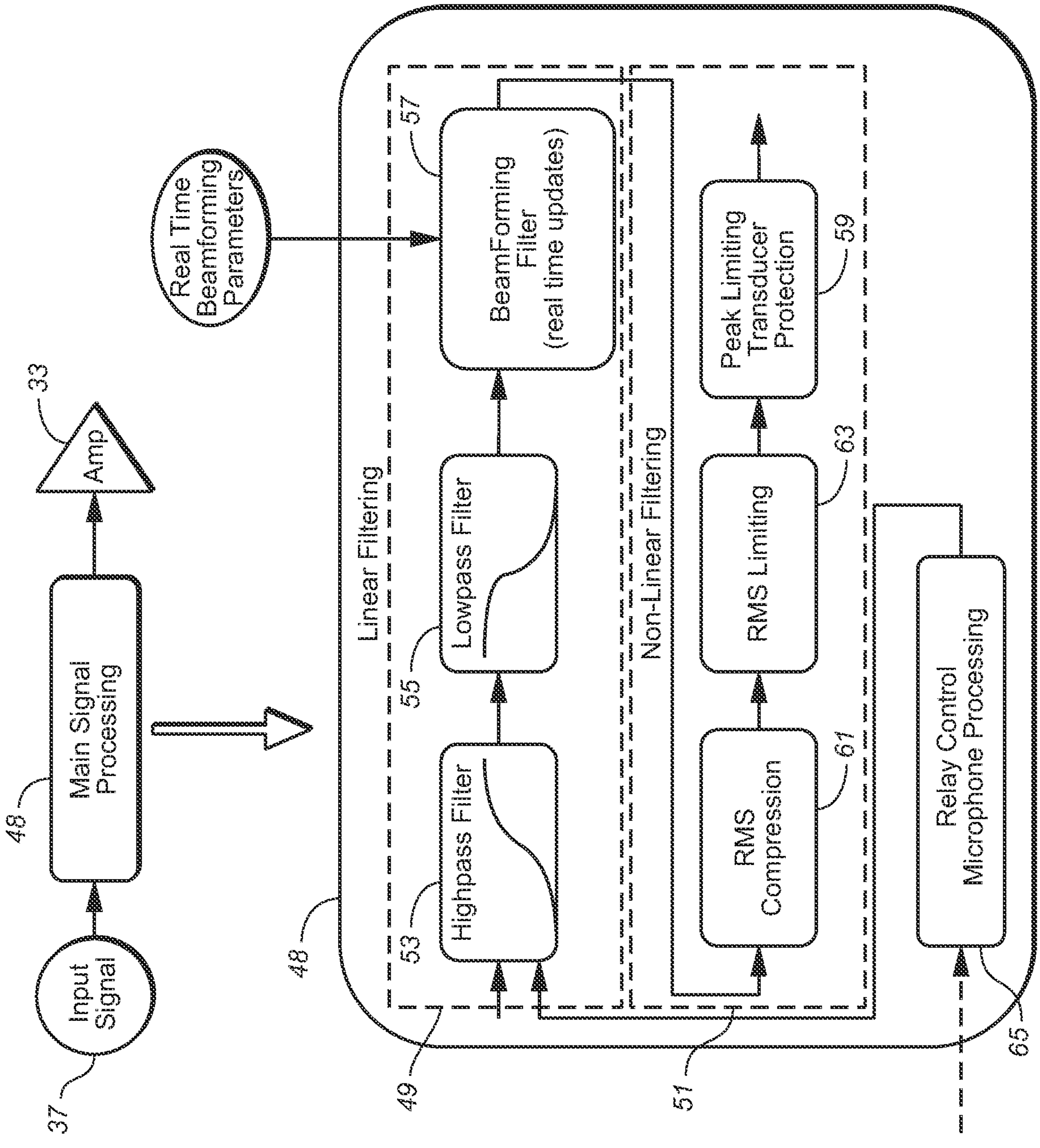
Input Signal
37
Main Signal Processing
48
Amp
33
Real Time Beamforming Parameters
48
Linear Filtering
49
Highpass Filter
53
Lowpass Filter
55
BeamForming Filter (real time updates)
57
Non-Linear Filtering
51
RMS Compression
61
RMS Limiting
63
Peak Limiting Transducer Protection
59
Relay Control Microphone Processing
65

FIG. 14

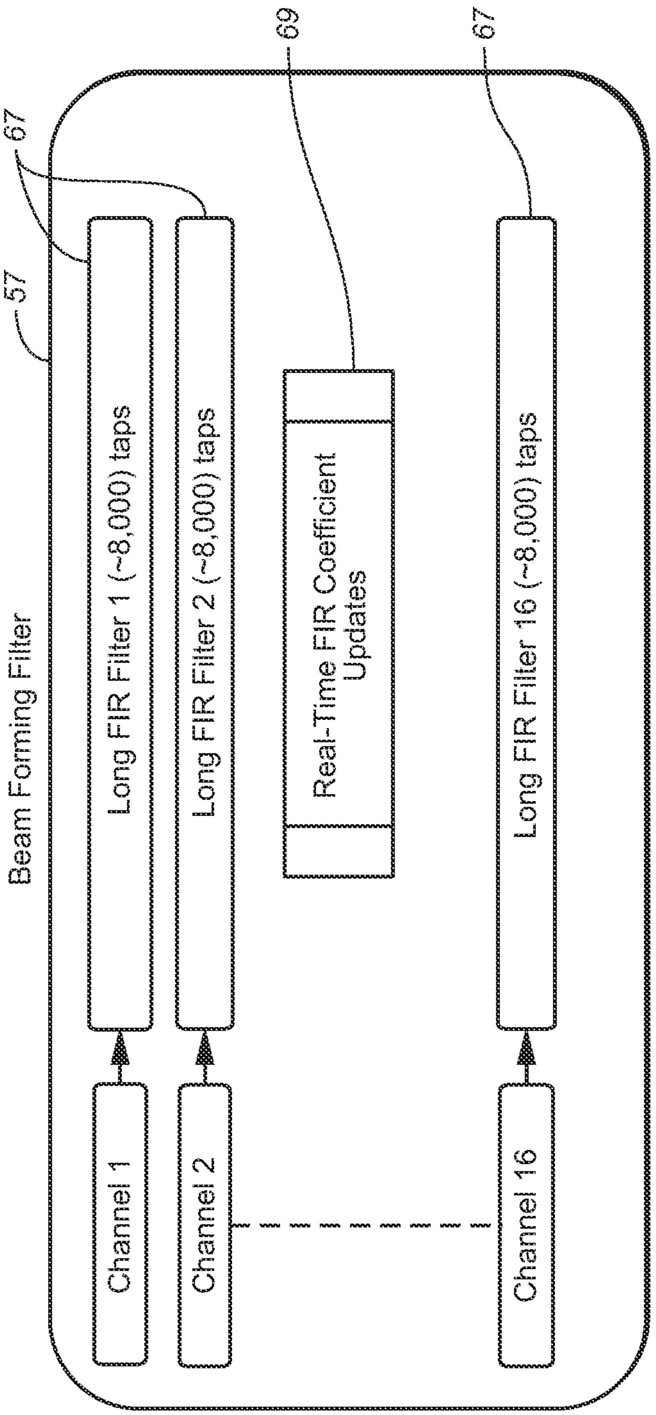
Beam Forming Filter
57
67
67
69
Long FIR Filter 1 (~8,000) taps
Long FIR Filter 2 (~8,000) taps
Real-Time FIR Coefficient Updates
Long FIR Filter 16 (~8,000) taps
Channel 1
Channel 2
Channel 16

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 21/43223

A. CLASSIFICATION OF SUBJECT MATTER

IPC - H04R 1/20, 1/32, 1/26, 3/12, 5/02 (2021.01)

CPC - H04R 1/20, 1/323, 1/32, 1/26, 3/12, 5/02, 2201/401, 2201/403, 2430/20; H04S 7/30

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y --- A	US 2017/0295418 A1 (CURTINSMITH et al.) 12 October 2017 (12.10.2017) entire document, especially Fig. 1 and 2, [abstract], para [0015], [0038], [0040]-[0042]	1-4, 8-14, 17, 18 --- 5-7 --- 15, 16
Y	US 2003/0029670 A1 (SMITH et al.) 13 February 2003 (13.02.2003) entire document, especially Fig. 4, para [0015], [0044]	5-7
A	US 2008/0212805 A1 (FINCHAM) 04 September 2008 (04.09.2008) entire document, especially Fig. 2A, para [0061]	15, 16
A	US 2006/0204022 A1 (HOOLEY et al.) 14 September 2006 (14.10.2006) entire document, especially para [0046]	15, 16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 September 2021	OCT 26 2021
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Kari Rodriquez Telephone No. PCT Helpdesk: 571-272-4300